SH@W Safety and Health at Work www.e-shaw.org

Saf Health Work 2011;2:236-42 | http://dx.doi.org/10.5491/SHAW.2011.2.3.236

pISSN : 2093-7911
eISSN : 2093-7997

Original Article

Prediction of Peak Back Compressive Forces as a Function of Lifting Speed and Compressive Forces at Lift Origin and Destination - A Pilot Study

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Objectives: To determine the feasibility of predicting static and dynamic peak back-compressive forces based on (1) static back compressive force values at the lift origin and destination and (2) lifting speed.

Methods: Ten male subjects performed symmetric mid-sagittal floor-to-shoulder, floor-to-waist, and waist-to-shoulder lifts at three different speeds (slow, medium, and fast), and with two different loads (light and heavy). Two-dimensional kinematics and kinetics were captured. Linear regression analyses were used to develop prediction equations, the amount of predictability, and significance for static and dynamic peak back-compressive forces based on a static origin and destination average (SODA) back-compressive force.

Results: Static and dynamic peak back-compressive forces were highly predicted by the SODA, with R^2 values ranging from 0.830 to 0.947. Slopes were significantly different between slow and fast lifting speeds ($p < 0.05$) for the dynamic peak prediction equations. The slope of the regression line for static prediction was significantly greater than one with a significant positive intercept value.

Conclusion: SODA under-predict both static and dynamic peak back-compressive force values. Peak values are highly predictable and could be readily determined using back-compressive force assessments at the origin and destination of a lifting task. This could be valuable for enhancing job design and analysis in the workplace and for large-scale studies where a full analysis of each lifting task is not feasible.

Key Words: Lifting, Biomechanics, Linear models, Workplace, Risk assessment

Introduction

Back-compressive forces (BCF) have been used to assess spinal loading during manual material handling (MMH) tasks, especially those at the L5/S1 interface [1]. Guidelines proposed by the Work Practices Guide for Manual Lifting say, "biomechanical compression forces on the L5/S1 disc are not tolerable over 650 kg (1430 lb) in most workers" and "a 350 kg (770 lb) compression force on the L5/S1 disc can be tolerated by most young, healthy workers" [2]. These limits were established primarily through compression testing of cadaver vertebral segments, and did not consider inertial forces. In 1997, the National Institute for Occupational Safety and Health (NIOSH) reviewed epidemiologic evidence of the relationship of low-back disorders to (1) heavy physical work, (2) lifting and forceful movements, (3) bending and twisting (awkward postures), (4) whole-body vibration, and (5) static work postures. It was reported that "there is strong evidence that low-back disorders are associated with work-related lifting and forceful movements" [3].

Received: February 28, 2011, **Revised:** June 8, 2011 **Accepted:** June 8, 2011
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Most models used to predict the physical demands and musculoskeletal risk of job tasks require an accurate representation of the worker posture to perform an accurate analysis. One problem that exists when applying ergonomic tools occurs when an analyst attempts to measure the posture of a worker in motion. Measuring posture in the workplace has proven to be difficult and a source of potential errors resulting in misleading results from model outputs [4-6]. Many of these models are assessments made of static events and neglect the dynamic nature of lifting during manual material handling tasks. It has been argued that inertial loads significantly increase the magnitude of biomechanical forces, but their relationship to low back musculoskeletal disorders is unclear [7-9].

Numerous researchers have found dynamic calculations to be superior to corresponding static calculations for predicting BCF [8,10,11]. Static calculations at any speed yield identical results for BCF if postures are the same. Dynamic BCF calculations differ if the speed of the MMH task is different, due to dissimilar accelerations and decelerations of the load, even if postures are the same between lifts.

The purpose of this investigation was to determine the feasibility of predicting static and dynamic BCF based on static BCF calculations at the origin and destination of a mid-sagittal symmetric lifting task. By establishing the relationship between BCF of the origin and destination of a lift and a BCF for a total lift cycle, it was hypothesized that acceptable estimates of peak and cumulative BCF could be made without the need for more complex and costly motion analysis techniques. Additionally, it was desirable to understand the effect of lifting speed on these predictions.

Materials and Methods

Subjects

Ten adult male subjects comprised the study population with a mean (± standard deviation [SD]) age of 27.5 (4.1) years, mean height of 175.6 (5.6) cm, and mean weight of 73.8 (9.3) kg. All were free from injuries or other disorders which would affect their ability to perform the lifting tasks. Each participant signed a consent document before participating in the study which informed them of study methods and possible risks of participation. The University of Utah Institutional Review Board approved this study.

Data acquisition

Reflective markers were attached unilaterally on the left side of a participant at the following locations: head, acromium process, lateral epicondyle of the humerus (elbow joint), distal radius (wrist joint), center of the hand, sacrum, greater trochanter, femoral condyle, malleolus, calcaneous, and metatarsal head. Two-dimensional motion data was captured at 60 Hz with one Panasonic GS-55 digital camcorder. A 6-axis AMTI force plate (Advanced Mechanical Technologies, Inc., Watertown, MA, USA) recorded ground reaction force at 600 Hz and was used to verify dynamic loads for each lifting speed. ViconMotus (Vicon, Centennial, CO, USA) software was used to obtain and process camera and force plate data and to compute both static and dynamic compressive forces. Data was filtered using a 4th order zero lag Butterworth filter.

There were three independent variables studied for the sagitally symmetric lifting conditions: hand load (2.25 and 9 kg), lift type (floor to waist, waist to shoulder, and floor to shoulder), and lift speed (fast, medium, and slow). A rigid plastic box (33 cm width × 33 cm length × 28 cm height) with handles was loaded with weights to achieve the target hand loads. The hand loads selected for study were relatively low to reduce the potential risk of fatigue and injury from fast, frequent lifting. In total, each subject performed 3 repetitions for all 18 lifting conditions, consisting of a combination of the three lifting variables. Lifting conditions were randomized for each subject to minimize bias. Subjects were allowed to rest briefly between lifting conditions and were allowed a ten-minute rest period midway through data collection, if desired, to reduce bias due to fatigue.

Fig. 1 shows the dimensions of the test setup including vertical and horizontal dimensions for each shelf. The shelves were 87 cm in width with the uppermost shelf being at shoulder height and the lowest shelf at waist height. The shelves extended back into a bookshelf with ample room for the plastic

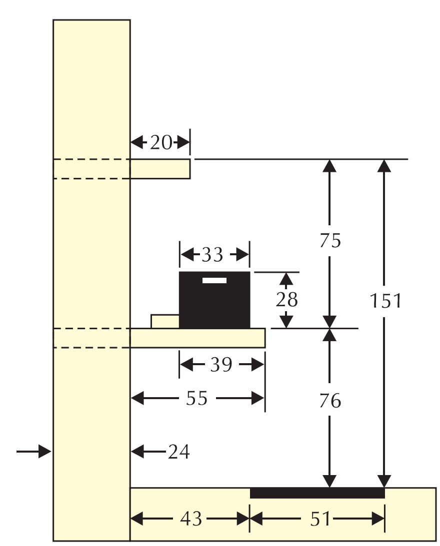

Fig. 1. Vertical shelf locations for each lift type (dimensions in cm).

box to fit on each top shelf. The force plate is also included in Fig. 1 as a black rectangle, having a width of 51 cm.

The 20 cm shelf depicted in Fig. 1 was always the destination shelf regardless of lift type, while the 55 cm shelf was only used for the waist-to-shoulder lift. Subjects stood on the force plate, but were given no specific guidance in terms of a distance to position themselves from the shelves.

Average lifting velocity calculated by the change in vertical location over time (herein referred to as lifting speed) was controlled using a metronome. Slow and fast lifting speeds of 0.375 and 0.75 m/s (100% faster), respectively, were based on those suggested by earlier research on lifting speeds [12]. For each lifting condition, the subjects attempted to lift at the speed indicated by the metronome by beginning the lift on a beat and ending the lift on the subsequent beat. Researchers began recording data when the actual lifting speed and the metronome beats were closely matched. Data collection continued for several cycles.

Data analysis

ViconMotus software was used to process the motion and force plate data to calculate kinematics and kinetics. Locations of centers of mass were estimated based on anthropometry [13,14]. Additional joint and muscle locations were estimated from published literature [15,16]. The origin and destination of each lift cycle was identified within each lifting trial. Three lift cycles were averaged to comprise a composite lifting cycle for every lifting condition. The composite lifting cycle was normalized to establish a 100% lift cycle for direct comparison of lifting speeds between subjects, lift types, and speeds.

Forces and moments of interest were calculated with both static and dynamic equations to evaluate the effects of lifting speed on forces and moments at the low back. The following equations were used to calculate the static and dynamic BCF based on motion and force data:

$$BCF_{static}(\mathrm{N}) = MF + (\cos[40] \times [L + m_{UB}]) \times \mathrm{g} \tag{1}$$

$$BCF_{dynamic}(\mathrm{N}) = MF + (\cos[40]) \times ([L(\mathrm{g} + a_L)] + [m_{UB} \times (\mathrm{g} + a_T)]) \tag{2}$$

where L is the load in the hands, g is gravity, a_L is the acceleration of the hands, a_T is the acceleration of the trunk, m_{UB} is the mass of the upper body, and MF is the erector spinae muscle force. The term cos(40) represents the assumed 40 degree L5/S1 vertebral interface angle with respect to the horizontal. The differences between the static and dynamic calculations are that the acceleration terms for each mass are accounted for in the dynamic equations, but are not included in the static equations. The influence from Coriolis acceleration was neglected. MF is calculated by:

$$MF = \frac{M_{L5S1}}{D_{ES}} \tag{3}$$

where M_{L5S1} is the sum of the moments about the L5/S1 interface and D_{ES} is the perpendicular distance from the L5/S1 interface to the erector spinae muscle group and represents the muscles' effective moment arm. In the present study, D_{ES} was approximated as 6.86 cm [14,17]. The erector spinae muscles were assumed to act at a perpendicular moment arm of 6.86 cm to the L5/S1 interface. Additionally, the erector spinae muscles were assumed to be the sole contributors to resist the moment about the L5/S1 joint. The moment about the L5/S1 joint was calculated by multiplying distances from the center of mass of body segments to the L5/S1 joint by the mass of those segments. Inertial forces due to motion of the forearm, upper arm, torso, and hand loads were neglected for the static model, but were included in the dynamic model.

BCF values were normalized by body weight. Normalization techniques are often used in gait analysis [18-20] and are practical for making direct comparisons between individuals with different anthropometry for evaluating lifting tasks.

Statistical analysis

Static BCF values for the lift origin and destination were averaged for every lifting condition and subject. Static origin and destination average (SODA) values were compared to static and dynamic peak BCF values for the lift using linear regression analyses. The slope and intercept of the regression line was computed for each lifting speed. R^2 values were computed. One discordant point was discarded from the analyses. Statistics were performed using IBM SPSS Statistics 19 (IBM Corporation, Somers, NY, USA). Results were considered statistically significant when $p < 0.05$ ($\alpha = 0.05$).

Results

Subjects performed a set of 3 repetitions for all 18 lifting conditions. This resulted in mean (± SD) velocities of 0.64 (0.17), 0.44 (0.13), and 0.34 (0.07) m/s for fast, medium, and slow lifts, respectively. The slope of the regression lines indicates the ratio of the peak BCF to the SODA. Slopes greater than one indicate under-prediction of peak values.

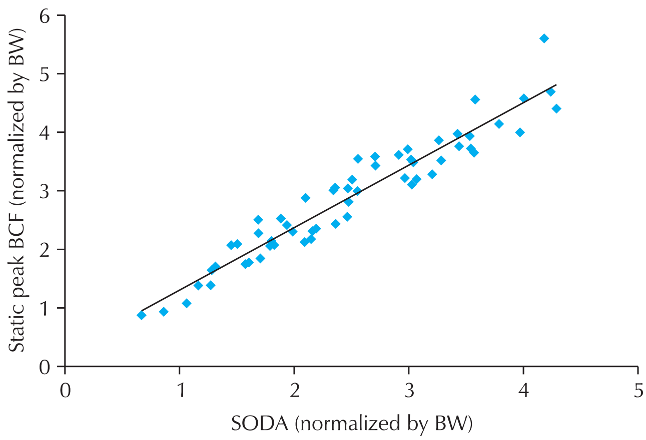

Fig. 2. Overall linear regression of SODA vs. static peak BCF. SODA: static origin and destination average, BCF: back-compressive forces, BW: body weight.

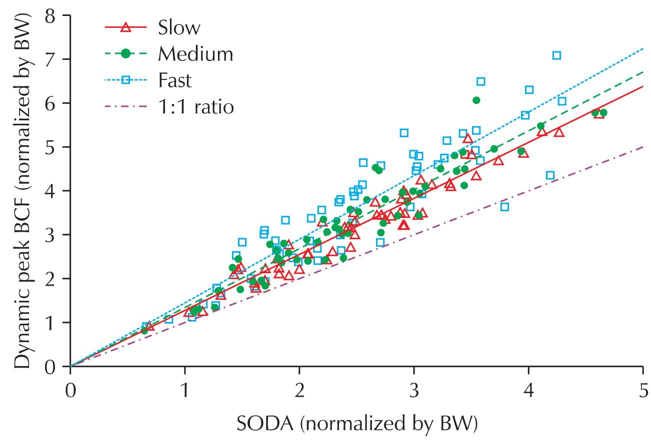

Fig. 3. Linear regression lines - SODA vs. dynamic peak BCF for various lifting speeds. SODA: static origin and destination average, BCF: back-compressive forces, BW: body weight.

Table 1. Linear regression results - SODA vs. static peak BCF

	R^2	Slope		Intercept	
		Value	Std. error	Value	Std. error
Slow	0.937	1.047*	0.036	0.279†	0.092
Medium	0.926	1.025*	0.038	0.323†	0.098
Fast	0.917	1.061*	0.042	0.247†	0.112
All speeds	0.926	1.045*	0.022	0.283*	0.058

SODA: static origin and destination average, vs: versus, BCF: back-compressive forces, Std: standard.
*Statistically significant ($p < .001$), †Statistically significant ($p < .05$).

Table 2. Linear regression results - SODA vs. dynamic peak BCF

	R^2	Slope		Intercept	
		Value	Std. error	Value	Std. error
Slow	0.947	1.274*	0.040	-0.015	0.102
Medium	0.907	1.343*	0.056	-0.026	0.146
Fast	0.830	1.449*	0.087	-0.010	0.230
All speeds	0.867	1.363*	0.040	-0.037	0.105

SODA: static origin and destination average, vs: versus, BCF: back-compressive forces, Std: standard.
*Statistically significant ($p < .001$).

SODA BCF vs. static peak BCF

The slope of the regression line predicting static peak BCF from SODA was significant for each lifting speed individually, and when all lifting speeds were grouped together. A plot of all speeds grouped together is shown in Fig. 2, with an R^2 value of 0.926. The slope was significantly greater than one ($p < 0.05$), at a value of 1.045. A summary of linear regression results is shown in Table 1.

SODA BCF vs. dynamic peak BCF

The slope of the linear regression line predicting dynamic peak BCF from SODA was significant for all three lifting speeds ($p < .001$). Slopes were 1.274, 1.343, and 1.449 for slow, medium, and fast lifting speeds, respectively. The regression lines are shown in Fig. 3, along with a line having a slope of one. The intercept was not statistically significant at any lifting speed. R2 values were 0.947, 0.907, and 0.830 for slow, medium, and fast lifting speeds.

When all lifting speeds were grouped together, R^2 for the linear regression was 0.867 with a statistically-significant slope of 1.363 ($p < .001$). Additionally, the slope of the regression line for the slow speed is significantly different than the slope for the fast speed ($p < 0.05$). Table 2 is a summary of the results from the linear regression analyses for dynamic peak BCF.

Discussion

For mid-sagittal symmetric lifting of up to 20 lbs, dynamic peak BCF can be accurately predicted using static BCF calculated at the origin and destination of the lift cycle. Nearly 95% of the variability in dynamic BCF can be predicted by the SODA at a slow lifting speed and over 90% at a medium lifting speed. This high predictability is maintained without accounting for the lift type or load magnitude in the regression equations. It should be noted that as lifting speed increases the R^2 values decrease because the variability in lifting speed also increases with lifting speed.

Intercepts for the regression lines are nearly zero for all lifting speeds and are not statistically different from one another. The intercept has a minimal effect on the prediction of dynamic peak BCF and might be an unnecessary part of the prediction equation. It is noteworthy to mention that there is a statistically-significant difference between the slopes for slow and fast lifting speeds of 13.7%. When attempting to accurately predict dynamic peak BCF values based on SODA, it is important to determine and incorporate the lifting speed into the prediction equations for more accurate results.

When lifting speed was ignored and all values were lumped together, 86.7% variance in dynamic peak BCF, a large amount, was predicted by SODA. The intercept was not significantly different than zero. This overall prediction equation could be used beneficially for a large range of lifting speeds to determine dynamic BCF values based on measurements of static postures.

For each lifting speed and for the overall case, the slopes of the prediction equations for dynamic peak BCF are statistically greater than 1.0 ($p < 0.05$). The same is true for the overall static case. In the present study, the average normalized SODA is 2.42. At this value the static peak BCF is under-predicted by SODA by 7% to 22% ($p < 0.05$), based upon the 95% confidence interval for the regression line. For the overall dynamic case it can be ascertained that the dynamic peak is under-predicted by 28 to 44% ($p < 0.05$).

Errors in computing BCF or determining peak BCF values could lead to misclassification of risk based on BCF guidelines, such as those suggested by the NIOSH Work Practices Guide, particularly when values are nearing a proposed limit. It is vital to use an accurate BCF model when the hazard level of a task or job is being determined based on those calculations. Other errors resulting from attempts to measure the posture during a dynamic lift may also be avoided by measuring the location of an object at the origin and destination of a lift relative to the L5/S1 [5,14].

Peak BCF prediction techniques can be advantageous for workplaces with many different tasks or for large-scale studies where BCF is analyzed. Based on the results of our study, a good estimate for static or dynamic peak BCF could be computed without analyzing the entire lift cycle. As a result, peak BCF predictions can be both accurate and efficient if the nominal BCF calculations are accurate.

Normalization techniques for BCF used in this study are beneficial because they allow for simple adaptation of BCF values for persons with different anthropometry. Applied to workplace design, workspaces could be designed with multiple anthropometries in mind to ensure that peak BCF values are acceptable no matter the anthropometry. Decreasing the BCF at either the origin or the destination of the lift will decrease the peak BCF seen during the lift.

The participant population of ten male subjects, whose anthropometry did not vary widely, is more characteristic of a pilot study than a cohort study. There might be larger variations in results for individuals with different anthropometry and also differences for females. While the prediction equations determined in this study were developed using this subject population, it is proposed that this study provides the basis for a larger study with more breadth in terms of participants and scope from which more encompassing prediction equations can be developed.

Other future work might include applying prediction equations to datasets from large cohort studies of workplace risk for low-back pain to further evaluate the effectiveness of the proposed technique, and its relationship to lower back disorders. Consideration should be given to incorporate lifting speed into current, widely available analytical tools that predict BCF (University of Michigan Three-Dimensional Static Strength Prediction Program, Utah Back Compressive Force Model) or those that deal with a more general risk metric (NIOSH revised lifting equation, Snook Liberty Mutual Tables). A method would need to be developed that would allow for rapid determination of lifting speed with little or no training in order to do this.

After five subjects had participated in the study, a mechanical "stop" was added to the shelves (displayed in Fig. 1) to help researchers identify the beginning of the lift cycle for the remaining five participants. This improved the consistency of the starting location of the hands for the waist-to-shoulder lift. Horizontal origin and destination distances can greatly influence BCF due to changes in moment arms and were not well controlled in this study. This limitation could be addressed in future work by including horizontal origin and destination distances as independent variables in the study protocol. Additionally, the horizontal distance from the subject to the shelves could be controlled to a much greater extent.

Slow, medium, and fast speeds were controlled by allowing participants to adjust to a metronome. Although the participants aimed to match the metronome, small errors resulted. Additional errors occurred due to adjustments during the lift cycle as participants slowed down towards the end of a lift to try and make a lift longer. As was mentioned previously, researchers tried to minimize this speed error by allowing participants to lift a number of cycles until they became accustomed to that speed before collecting data. Lifting speeds in this study were different than the target values for slow and fast lifts as defined in the methods section. It should be noted that the lifting tasks were not performed at constant velocity. During a lifting task there are periods where the load is accelerated (the beginning of the lift cycle) and periods of load deceleration (the end of the lift cycle). These accelerations and decelerations are ultimately what make dynamic BCF different than the static BCF for the lifting task. Additionally, the peak static BCF does not occur at the lift origin or destination, so the peak dynamic (or static) BCF will be larger than the SODA.

The present study is limited in that the maximum hand load was 9 kg (around 20 lbs). This was done to minimize risk of injury and fatigue to participants. In industrial tasks, loads are often in excess of 9 kg. It could be beneficial to model or conduct a study in which higher loads are used in order to develop predictive equations that would be more applicable to industrial settings without extrapolation. There are dangers inherent in extrapolating prediction equations created at relatively low loads to high load situations. However, unless lifting posture changes significantly as a function of increased load, the prediction equations developed in this study would still be applicable.

Motion-collection techniques using cameras and reflective markers are subject to small errors resulting from marker placement, skin motion, and camera resolution. Additionally, in this two-dimensional study a one-sided marker set and only one video camera were used to capture and analyze data, with symmetry assumed. This may have led to additional errors in terms of marker location compared to actual underlying anthropometry, and inaccuracies due to minor asymmetry in lifting. There may be slight errors in the overall quantification of BCF, but the results show merit in predicting BCF based on SODA and the lift speed.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgments

This work was supported in part by the Rocky Mountain Center for Occupational and Environmental Health at the University of Utah. The Rocky Mountain Center, an Education and Research Center, is supported by Training Grant No. T42/OH 008414 from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health. The contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Institute for Occupational Safety and Health. The research was conducted in the Ergonomics and Safety Lab at the University of Utah. Many graduate students in the Ergonomics and Safety Lab contributed to data collection and processing.

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